Turbulent Mixing in Oceanic Surface and Benthic Boundary Layers

H.J.S. Fernando
Environmental Fluid Dynamics Program
Department of Mechanical & Aerospace Engineering
Arizona State University, Tempe, AZ 85287-9809
phone: (602) 965-2807 fax: (602)-965-8746 email: j.fernando@asu.edu
Award #: N00014-97-0070
http://www.eas.asu.edu/~pefdhome

LONG-TERM GOALS

The long-term goal of our research program is to understand, using laboratory experiments, numerical modeling and theoretical analysis, small-scale mixing processes occurring in oceanic surface and benthic boundary layers. The knowledge so gained will be used to develop sound closure parameterizations for prognostic numerical ocean circulation models.

SCIENTIFIC OBJECTIVES

The objective of the work being reported was to improve the fundamental knowledge of turbulent mixing and diffusion processes occurring in oceanic boundary layers, especially surface wind-mixing layer and wave-current boundary layer in coastal oceans. In the studies of surface mixed layers, the focus was on the penetration of a turbulent layer into a density stratified layer and associated turbulent momentum and mass transfer processes. Also of interest were the effects of such transports on large-scale circulation patterns and air-sea coupling. The study on the wave boundary layer is expected to verify the accuracy of commonly used bottom boundary-layer parameterizations of coastal ocean models.

APPROACH

A major part of the study on the penetration of a turbulent mixed-layer into a stratified layer was laboratory experimental. The experiments were performed in a recirculating water channel, whereby an upper turbulent layer was driven over a stagnant denser layer to mimic the development of upper-ocean mixed layer. A specially designed disk pump was used to drive the flow, and precautionary measures were taken to ensure one-dimensional growth of the mixed layer. Detailed measurements using the laser-Doppler, hot film and particle-tracking velocimetry techniques as well as flow imaging using the laser-induced fluorescence (LIF) method were used for flow diagnostics. The measurements included the production of turbulent kinetic energy, turbulent stresses, buoyancy flux, rate of dissipation, internal wave radiation, integral-scales of turbulence and the local Richardson number with a resolution of 2.5 mm (using a specially designed probe). Most of these data were taken during the previous year, and the FY97 was essentially dedicated to analyze the data and place the results in the context of existing theories, parameterizations and concepts on oceanic turbulence. This work was conducted by Dr. Eric Strang as a part of his Ph.D. thesis under the supervision of P.I.

Two approaches were used to study the physics and transport properties of wave boundary layers. In the first approach, a purely oscillatory turbulent boundary layer, generated by an oscillating bottom in a deep fluid layer, was used to mimic the oscillatory flow under waves. Also, the capability of imposing a mean flow on the oscillatory boundary layer was also established. This work is being

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **1998**	2. REPORT TYPE	3. DATES COVERED **00-00-1998 to 00-00-1998**
4. TITLE AND SUBTITLE **Turbulent Mixing in Oceanic Surface and Benthic Boundary Layers**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Arizona State University,Department of Mechanical & Aerospace Engineering,Environmental Fluid Dynamics Program,Tempe,AZ,85287-9809**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002252.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

performed by Ms. Rajka Krstic as a part of her Ph.D. thesis project. In the second investigation, carried out by Dr. Heather Earnshaw, an actual wave boundary layer produced by a periodic train of waves traveling on a sloping beach was investigated in a large wave tank of dimensions 104.5 x 3.5 x 6 (ft). In both of these studies, the parameters of interest were the mean velocity profiles, integral length and velocity scales of turbulence and the upward diffusion of turbulent kinetic energy, momentum and mass. Particle-image, particle-tracking and laser-Doppler velocimetry were used for flow diagnostics.

WORK COMPLETED

The experiments on the deepening of a turbulent mixed layer into a linearly stratified fluid were completed, and several papers have been already submitted for publication. A few additional papers are also in preparation, which will be submitted in the near future.

The work on oscillatory boundary layers was completed, which includes the evaluation of eddy viscosity as a function of the distance from the bottom and the phase of flow oscillations. Comparisons of measurements with available parameterizations and published data were made. Design and construction of an apparatus for studies on oscillatory boundary layer/mean current interaction were completed, and experiments are underway in this new facility.

RESULTS

Efforts to quantify buoyancy and momentum transports through stratified shear layers using our controlled laboratory experiments revealed some interesting features. It was found that these transport rates are primarily governed by the bulk Richardson number $Ri_B = \Delta bD/\Delta U^2$, where ΔU and Δb are the velocity and buoyancy jumps across the shear layer and pycnocline, respectively, and D is the depth of the mixed layer overlying the sheared density interface. This bulk parameter, however, was closely related to the mean local gradient Richardson number $Ri_g = N^2/du/dz)^2$, where N is the local buoyancy frequency at the base of the mixed layer and du/dz is the local shear. When $Ri_B < 5$ (or $Ri_g < 1$), turbulent mixing at the shear layer was dominated by energetic Kelvin-Helmholtz billows, the breakdown of which produced strong, intermittent buoyancy transport episodes. Mixing in the stratified shear layer appears to be most efficient, with a mixing efficiently of $Ri_f = 0.4$, at the critical Richardson number of $Ri_g =1$ (or $Ri_B = 5$). The range of flux Richardson numbers Ri_f observed ($0.05 < Ri_f < 0.4$) is consistent with that of $Ri_f = 0.15$ commonly employed in the Osborn dissipation model and those found in various oceanic data, namely, $Ri_f \sim 0.15 -0.2$ in turbulent patches within the main thermocline (Moum & Osborn 1986) and $Ri_f \sim 0.4$ in turbulent tidal fronts (Gargett & Moum 1995); see Figure 1. Correspondingly, the dissipation flux coefficients (the ratio of buoyancy flux to the dissipation rate) measured in our experiments showed an excellent agreement with those obtained in turbulent tidal fronts and a reasonable agreement with data obtained from oceanic (turbulent) surface layers.

Above the critical value of $Ri_g >1$, the mechanism responsible for turbulent mixing

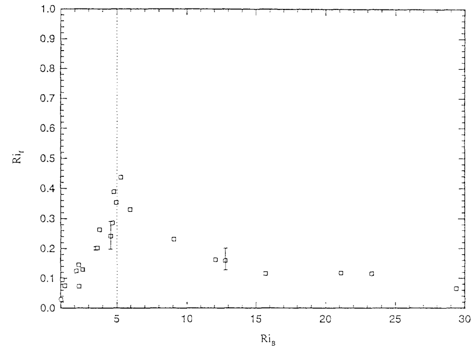

Figure 1: Variation of flux Richardson number Ri_f with Ri_b.

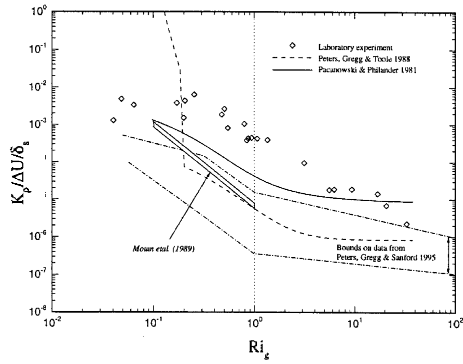

Figure 2: Non-dimensional form of eddy diffusivity for density K_ρ plotted versus Ri_g. The solid line indicates the model proposed by Pacanowski & Philander (1981). Here, δ_s is the thickness of the shear layer. The dashed line indicates the model proposed by Peters, Gregg & Toole (1988). The dashed -dotted line shows the bounds on data reported in Peters, Gregg & Sanford (1995).

transitions from K-H to intermittent breaking of interfacial (internal) waves and secondary shear (Holmboe) instabilities. Crossing to this new regime is associated with a dramatic reduction of the entrainment rate, almost by an order of magnitude. The laboratory observation of a critical Richardson number (Ri_g =1) is consistent with limited ocean observations available (Moum et al. 1992). Furthermore, it is in fair agreement with mixing shut-off criteria employed in some integral mixed-layer models (Price et al. 1986).

Measurements performed vertically across the stratified shear layer were used to estimate the eddy diffusivities of density and momentum, K_ρ and K_m, respectively. When properly scaled, comparisons of these values with those deduced by oceanic microstructure measurements and several expressions used for oceanic mixing parameterizations indicate a fair agreement; see Figure 2. Laboratory data, however, were typically larger than upper bounds of these estimates. When mixing is active, $Ri_B < 5$ (or $Ri_g < 1$), K_ρ was found to be approximately equal to K_m; this assumption is commonly used in numerical models at all Ri_B, although our data show that, at large Ri_B, the momentum transfer coefficients are higher than its buoyancy transfer counterpart.

Turbulent wave-boundary layer studies carried out with an oscillating bed (with a sinusoidal velocity) in the absence of a mean current included measurements of the boundary-layer thickness, shear

stress, eddy viscosity, turbulent kinetic energy and integral length scales.

Flow visualization elicited the mechanism of vortex formation surrounding roughness elements, which occurred at the end of each half-cycle (Figure 3). Vortices so formed interacted with surrounding vortices within the boundary layer, causing violent exchange of the mass and momentum in the vertical direction. Turbulent kinetic energy was found to be maximum near the bed, and its distribution followed the numerical calculations of Justensen (1988) reasonably well. Measurements over two-dimensional planes enabled the calculation of autocorrelation functions of velocity at different distances from the bed for different phases of flow oscillations. Comparison of eddy viscosity measurements with the theoretical model of Trowbridge and Madsen (1984) and the integral length scale measurements with the model of Grant & Madsen (1979) elicited successes and failures of these models. For example, integral length-scale measurements agreed fairly well with the predictions of Grant & Madsen (1979), usually within 10%, indicating their suitability to parameterize lengthscales in numerical models (Figure 4). As a continuation of this work, experiments are now being conducted on wave-current boundary layers. A specially designed apparatus, capable of superimposing a steady (mean) current on the oscillatory motion is used for this purpose. This study is expected to yield important new information on the modification of current (mean velocity, shear stresses, roughness length and integral velocity and lengthscales) by the oscillatory component of the boundary layer. The results will be compared with the theoretical model of Grant & Madsen (1979).

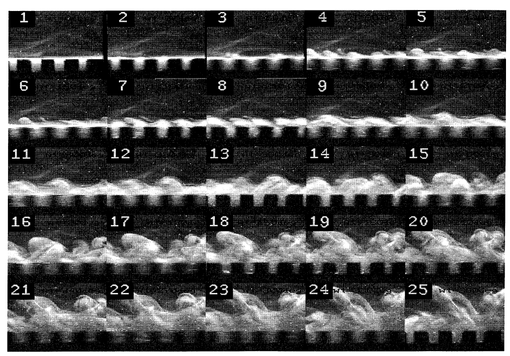

Figure 3: The formation of vortices in an oscillatory flow above a rough bed. Amplitude and period of oscillations are 10cm and 5s, respectively, and the roughness height is 4.8mm. Phase difference between the pictures are 30 deg (starting from 0 deg).

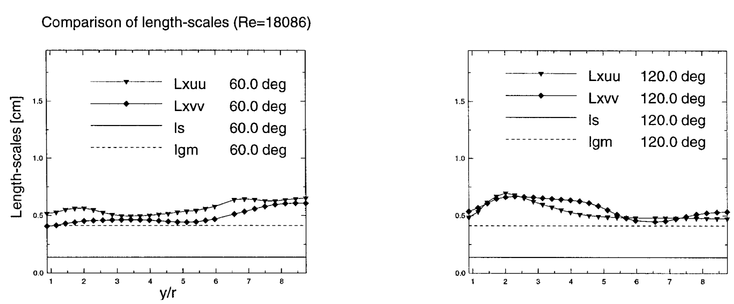

Figure 4: Comparison of measured (horizontal) integral length scales of horizontal and vertical velocity components, Lxuu and Lxvv, with the predictions of Grant & Madsen (1979) lgm and the Stokes boundary-layer thickness ls.

IMPACT/APPLICATIONS

The results of stratified shear-layer studies are of immense utility in refining existing mixed-layer models and for establishing the viability of commonly used eddy-diffusivity parameterizations. Oceanic mixed layer is a key entity for a hierarchy of ocean models, ranging from one-dimensional local models to large-scale climate models. In all atmosphere-ocean models, the air-sea coupling is realized through the mixed layer, and hence the accuracy of such models hinges on mixed-layer parameterizations. Our results show that certain parameterizations employed in current models can be improved, based on insights gained from laboratory and theoretical modeling work. Laboratory-based parameterizations are currently being tested in two numerical models, one is an in-house built one-dimensional mixed-layer model (Fernando et al. 1998) and the other is a meso-scale atmospheric flow model (HOTMAC) originated at the Los Alamos National Laboratory. The results of the oscillatory boundary layer studies show that some existing parameterizations are inadequate to accurately account for the turbulent transfer of momentum through wave boundary layers.

TRANSITIONS

As stated before, the eddy-diffusivity parameterizations based on our work are being utilized to modify the HOTMAC code for mesoscale atmospheric flows developed at the Los Alamos National Laboratory. Also, the observation of sharp reduction in the entrainment rate beyond a threshold Richardson number can be a powerful result that can be implemented in representing intense mixing events in numerical ocean models. As pointed out by Skyllingstad et al. (1996), in most OGCM's the ocean mixed layer is predicted by assignment of mixing coefficients that have little correspondence with reality, and hence they tend to produce erroneous results for mixed-layer depths (for example, the Community Modeling Effort of the World Ocean Circulation Experiment employed a constant vertical diffusivity and relaxation surface boundary conditions, which effectively prevented the deepening of the mixed layer!). Development of improved parameterizations appears to be the remedy for such problems.

RELATED PROJECTS

The P.I. is involved in a National Science Foundation project dealing with environmental turbulent flows. This project investigates general aspects of stratified shear flows and the descent of turbulent blobs of negatively buoyant fluid in such flows (thus mimicking atmospheric microbursts). Another project funded by the ONR coastal sciences program deals with the interaction of finite-sized objects with the coastal wave boundary layer.

REFERENCES

Fernando, H.J.S., Hunt, J.C.R., Strang, E.J., Berestov, A.L. and Lozovatsky, I.D. 1998: "Turbulent mixing in stably stratified flows: limitations and adaptations of the eddy diffusivity approach," In: Physical Processes in Lakes and Oceans, Coastal & Estuarine Studies (American Geophysical Union) Volume XXX, 334-347, 1998.

Justensen, P. 1988: Prediction of turbulent oscillating flow over rough beds. Coastal Engineering, 12, 257-284.

Gargett, A. E. and Moum, J. N. 1995: Mixing efficiencies in turbulent tidal fronts: Results from direct and indirect measurements of the density flux. J. Geophys. Res. 81, 1180-1196.

Grant, W.D. and Madsen, O.S. 1979: Combined wave and current interaction with a rough bottom. J. Geophys. Res., 80, 5109-5112.

Moum, J.N. and Osborn, T.R. 1986: Mixing in the main thermocline. J. Phys. Oceanogr. 16, 1250-1259.

Moum, J.N., Hebert, D., Paulson C.A. and Caldwell, D.R. 1992: Turbulence and internal waves at the equator. Part I: Statistics from towed thermistors and a microstructure profiler. J. Phys. Oceanogr., 22, 1330-1345.

Pacanowski, R.C. and Philander, S.G.H. 1981: Parameterization of vertical mixing in numerical models of the tropical oceans. J. Phys. Oceanogr. 11, 1443-1451.

Peters, H., Gregg, M.C. and Toole, J.M. 1988: On the parameterization of equatorial turbulence. J. Geophys Res. 93, 1199-1218.

Peters H., Gregg M.C., and Sanford T.B 1995: On the parameterization of equatorial turbulence: effect of fine-scale variations below the range of the diurnal cycle. J. Geophys. Res. 100(C9), 18333-18348.

Price, J.F., Weller R.A., and Pinkel, R. 1986: Diurnal cycle: Observations and models of the upper ocean response to diurnal heating, cooling and wind mixing. J. Geophys. Res., 91, 6411-8427.

Skyllingstad, E.D., Pualuszkiewicz, Denbo, D. and Smyth, W.D. 1996: Nonlinear vertical mixing processes in the ocean: modeling and parameterization. Physica D (98), 574-593.

Trowbridge J. and Madsen, O. 1984: Turbulent wave boundary layers II. Second-order theory and mass transport. J. Geophys. Res., 89, 7989-7997.

PUBLICATIONS

DeSilva, I.P.D. and Fernando, H.J.S. 1998: Experiments on collapsing patches in stratified fluids, *Journal of Fluid Mechanics,* **358**, 29-60.

Cole, G. and Fernando, H.J.S. 1998: Decay of turbulent fluctuations in a convecting boundary layer, *Fluid Dynamics Research*, **23(3)**, 161-176.

Manasseh, R., Ching, C.Y. and Fernando, H.J.S. 1998: The transition from wave-dominated to density driven isolated flows, *Journal of Fluid Mechanics,* **361**, 253-274.

Colomer, J., Zieren, L.D. and Fernando, H.J.S. 1998: Comments on the paper "Localized convection in rotating stratified fluid," *Journal of Geophysical Research*, **103(C6)**, 12,891-12,894.

Fernando, H.J.S., Chen, R-r. and Ayotte, B.A. 1998: Development of a point plume in the presence of background rotation, *Physics of Fluids*, **10(9)**, 2369-2383.

Fonseka, S.V., Fernando, H.J.S. and van Heijst, G.J.F. 1998: The evolution of an isolated turbulent region in a stratified fluid, *Journal of Geophysical Research* (accepted for publication).

Colomer, J. Casamitjana, X. and Fernando, H.J.S. 1998: Resuspension and sedimentation of particles

from a sediment bed by turbulent jets, *Applied Scientific Research,* (accepted for publication).

Berestov. A., Fernando, H.J.S. and Fox, P. 1998: Modeling of transport and seepage in effluent-dominated streams," *Journal of Water Resources Research* (accepted for publication).

Srdic-Mitrovic, A.N., Mohammed, N.A. and Fernando, H.J.S., 1998: Gravitational settling of particles through density interfaces, *Journal of Fluid Mechanics* (accepted for publication).

Strang, E.J. and Fernando, H.J.S.,1998: Turbulence and mixing in stratified shear flows, *Journal of Fluid Mechanics* (under revision).

Neves, J. and Fernando, H.J.S. 1998: Behavior of a sediment-laden vertical turbulent jet, *Journal of Fluid Mechanics* (under revision).

Lozovatsky, I. and Fernando, H.J.S. 1998: Observations of turbulence in marine stratified layers, *Journal of Geophysical Research* (under revision).

Wu, A. and Fernando, H.J.S. 1998: An analysis of fluid motions in and around differentially forced density interface, *Theoretical & Computational Fluid Mechanics* (under revision).

Fernando, H.J.S. and Buhler, J. 1998: The scales of sediment fingers, *Journal of Marine Research* (under revision).

Colomer, J. and Fernando, H.J.S. 1998: Resuspension of sediments by multiple vertical jets, ASCE Journal of Hydraulic Engineering (under revision).

DeSilva, I.P.D., Brandt, A., Montenegro, L.M. and Fernando, H.J.S. 1998: Gradient Richardson number measurements in a stratified shear layer. Dynamics of Atmosphere and Oceans (under revision).

Boubnov B.M. and Fernando H.J.S. 1998: Experimental study of convection from isolated source of buoyancy (in Russian). Izvestia, Fluid Gas Mechanics, Submitted for Publication.

Boubnov B.M. and Fernando H.J.S., 1998: Convection from a local source of buoyancy, (in Russian), Dokl. RAS (Proceedings RAS), Submitted for Publication.

Voropayev, S.A., McEachern, B., Fernando, H.J.S. and Boyer, D.L. 1998: Large vortex structures behind maneuvering bodies in stratified fluids, Submitted for Publication.

Kit, E., Strang, E., Fernando, H.J.S. and Norton, H. 1998: Experiments on the development of K-H billows in stratified shear flows, Seventh European Turbulence Conference, in: Advances in turbulence VII (Ed. Uriel Frisch), Kluwer Academic Publishers.

Srdic-Mitrovic and Fernando, H.J.S., 1998: On the stratification drag, Second International Symposium on Environmental Hydraulics, Hong-Kong, Dec 16-18, Accepted.

Fernando, H.J.S. 1998: Convection in rotating fluids and its geophysical relevance, Proceedings of the Konstantin Federov Memorial Symposium, St. Petersburg., UNESCO Volume # x, in Press.

Lozovatsky, I.D. and Fernando, H.J.S. 1998: Turbulence in stratified patches on a shallow shelf, Proceedings of the Konstantin Federov Memorial Symposium, St. Petersburg., UNESCO Volume # x,

in Press.

Fernando, H.J.S., Hunt, J.C.R., Strang, E.J., Berestov, A.L. and Lozovatsky, I.D. "Turbulent mixing in stably stratified flows: limitations and adaptations of the eddy diffusivity approach," In: Physical Processes in Lakes and Oceans, Coastal & Estuarine Studies (American Geophysical Union) Volume XXX, 334-347, 1998.

Fernando, H.J.S. and Smith D.C. IV 1999 Small-scale processes in geophysical flows. In: Mixing in Geophysical Flows (Eds. P.F. Linden and J.F. Redondo), Submitted.